Detecting regional patterns of changing CO_2 flux in Alaska

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With rapid changes in climate and the seasonal amplitude of carbon dioxide (CO_2) in the Arctic, it is critical that we detect and quantify the underlying processes controlling the changing amplitude of CO_2 to better predict carbon cycle feedbacks in the Arctic climate system. We use satellite and airborne observations of atmospheric CO_2 with climatically forced CO_2 flux simulations to assess the detectability of Alaskan carbon cycle signals as future warming evolves. We find that current satellite remote sensing technologies can detect changing uptake accurately during the growing season but lack sufficient cold season coverage and near-surface sensitivity to constrain annual carbon balance changes at regional scale. Airborne strategies that target regular vertical profile measurements within continental interiors are more sensitive to regional flux deeper into the cold season but currently lack sufficient spatial coverage throughout the entire cold season. Thus, the current CO_2 observing network is unlikely to detect potentially large CO_2 sources associated with deep permafrost thaw and cold season respiration expected over the next 50 y. Although continuity of current observations is vital, strategies and technologies focused on cold season measurements (active remote sensing, aircraft, and tall towers) and systematic sampling of vertical profiles across continental interiors over the full annual cycle are required to detect the onset of carbon release from thawing permafrost.

carbon cycle | permafrost thaw | climate | Earth system models | remote sensing

The future trajectory of carbon balance in the Arctic–Boreal Zone (ABZ) is of global importance because of the vast quantities of carbon sequestered in permafrost soils (1). Climate warming threatens to increase permafrost thaw and release soil carbon back to the atmosphere as a positive feedback promoting additional warming (2). It is unclear whether the observed intensification of the northern high-latitude carbon cycle is dominated by plant productivity or microbial decomposition, both of which seem to be increasing (3–6). Although warming temperatures and C/N fertilization promote greening and higher summer productivity during the short, intense growing season, these same factors also drive increased emissions during the long cold season (3–5).

Detecting changes in ABZ carbon balance requires sustained observations over the full annual cycle. In the last decade, researchers have recognized the importance of year-round land–atmosphere CO_2 flux observations (3–5). Synthesis studies of these data show that increasing growing season uptake has been offset by stronger winter respiration. Measurements of atmospheric CO_2 collected from in situ and remote sensing instruments provide spatially and temporally integrated constraints of net CO_2 exchange on regional to pan-Arctic scales. In situ observations have been limited primarily to a small network of surface towers and infrequent, short duration airborne campaigns designed primarily to detect the pan-Arctic background CO_2 signal but have provided key evidence of ongoing large-scale changes in the structure and metabolism of the ABZ (6–9).

Airborne observations show a trend of increasing CO_2 seasonal cycle amplitude (difference between maximum spring CO_2 and minimum summer CO_2) (7), with additional analysis suggesting that enhancements in growing season photosynthetic intensity and summer uptake in boreal regions are the most likely source of amplification (8). Ground-based measurements of high-latitude background air show a trend toward earlier CO_2 buildup in fall, suggesting a shorter carbon uptake period (9). The ABZ, thus, seems to be transitioning toward both increased uptake early in the growing season and increased respiration in the cold season.

Despite these advances, several factors have limited the ability of current atmospheric CO_2 observing strategies to fully constrain ABZ carbon balance changes. (*i*) Background variability: long-range CO_2 transport from lower latitudes drives much of the high-latitude seasonal cycle (10, 11) and obscures local signals. (*ii*) Interannual variability: short-term CO_2 variability driven by year to year changes in ABZ carbon balance and long-range transport obscures slower, long-term changes driven by climate warming. (*iii*) Limited near-surface coverage: the CO_2 content of air above 3 km [~700 millibars (mb)] and poleward of 60° N is influenced primarily by processes in northern midlatitudes (30° N to 60° N), including a strong terrestrial influence in summer (12). Observations at altitudes above 4 km (e.g., 500 mb) are only weakly sensitive to the ABZ. (*iv*) Limited spatial coverage: the ABZ is characterized by strong spatial heterogeneity in plant functional type, permafrost

Significance

Dramatic warming in northern high latitudes has led to increased photosynthetic carbon uptake during the short, intense growing season; however, microbial decomposition of soil carbon and increased emissions during the long cold season may offset summer uptake and impart a positive feedback on the global climate system. We show that current airborne and satellite measurements of atmospheric CO_2 can accurately quantify summer uptake but are insufficient to detect regional changes in cold season emissions. As the potential for Arctic carbon budgets to become impacted by permafrost thaw and cold season emissions increases, strategies focused on year-round vertical profiles and improved spatial sampling will be needed to track carbon balance changes.

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extent, and climate (13). Spatial sampling with significantly greater density than available from current ground-based and aircraft observing systems is needed. (*v*) Limited seasonal coverage: climate warming has intensified seasonal carbon exchange in the ABZ, with increasing summer uptake offset by increasing winter emissions (3–6). Observations restricted to the growing season fail to capture this differential temporal response, such that key drivers of present and future carbon balance may go undetected.

Based on these limitations, CO_2 observations collected at multiple temporal (seasons and years) and spatial (horizontal and vertical) scales are needed for more accurate detection of regional carbon cycle changes in the ABZ. Here, we investigate seasonal carbon fluxes in Alaska using satellite and airborne observations from 2009 to 2013. We leverage remote sensing observations from the Greenhouse Gases Observing Satellite (GOSAT), airborne in situ observations from the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) and National Oceanic and Atmospheric Administration (NOAA) Arctic Coast Guard (ACG) flights, and weekly NOAA airborne vertical profile measurements at Poker Flat, AK (PFA) (see dx.doi.org/10.3334/ORNLDAAC/1325). Together, these measurements sample vertically resolved and column-averaged CO_2 dry air mole fractions (XCO_2) across the full annual cycle and contain sustained multiyear information spanning local, regional, and pan-Arctic spatial scales (Figs. S1, S2, and S3). We compare these data with atmospheric simulations driven by modeled terrestrial carbon fluxes for present and future climate to distinguish local biological processes from background variability and determine detectability of future carbon–climate feedbacks associated with permafrost thaw.

Materials and Methods

CARVE, ACG, PFA, and GOSAT datasets are described briefly here and in more detail in *S1: Observed CO_2*. CARVE campaign flights were conducted for periods of 2 wk/mo from May to September of 2012 and from April to October of 2013, with 4–10 flights per campaign and 75 total tracks collected from 2012 to 2013 (Fig. S1). CARVE surveys focus on the lowest 500 m above the surface, with frequent vertical profiles. ACG flights collect high-resolution CO_2 in situ concentration data across more than 50 flights and an average of three vertical profiles per flight from 2009 to 2013 from early March to late November (Fig. S2). ACG typically measures vertical profiles over boreal and Arctic Alaska on the same day. PFA is based on year-round, fixed location, high-resolution airborne CO_2 flask concentration data collected at 12 different altitudes [500–8,000 m above sea level (asl)] over the PFA Research Range northeast of Fairbanks, AK every 2–4 wk since 2000. GOSAT XCO_2 retrievals have produced full coverage of the growing season (April to September) and partial coverage of spring and fall shoulder seasons at Alaska to pan-Arctic scales since 2009 (Fig. S3).

All aircraft datasets are filtered for biomass burning using onboard CO measurements and a high CO screen of 150 parts per billion (ppb) and then, separated into mixing layer (ML) and free troposphere (FT) bins to examine local vs. long-range effects on CO_2 seasonality. We consider several factors in choosing the altitude to separate these layers. Comparison of 1-km bins from 0 to 7 km shows high sensitivity of vertical gradients to year, season, and dataset (Fig. S4 *A–C*). The level at which the ML is decoupled from the FT also varies but typically resides at 2–4 km. In general, the vertical gradient exhibits very similar seasonal structure independent of choice of averaging bins (Fig. S4 *D* and *E*). For this analysis, we choose 3 km, because it represents the highest daily extent of the layer of surface influence and the pressure level (700 mb) above which air from midlatitudes has the strongest influence (12). We average all available data in the lowest 3 km asl (>700 mb) for the ML and from 3 to 7 km asl (700–500 mb) for the FT, noting that the approximate ML sampling altitude below 3 km varies across datasets. We use all available airborne data from 8:00 AM to 8:00 PM local standard time (LST), but most data were collected from midday to 4:00 PM. We note a slight sensitivity of the vertical distribution and gradient of the CO_2 seasonal cycle to diurnal sampling biases (Fig. S5), which are likely attributed to diurnal variability in CO_2 flux and ML depth. We remove the secular trend and calculate spring and fall zero crossing dates as discussed in *S1: Observed CO_2*.

We simulate atmospheric CO_2 using the Goddard Earth Observing System Chemistry global tracer model (GEOS-Chem) (14) forced by assimilated meteorological fields and surface CO_2 flux from land, ocean, and fossil fuel sources. Monthly CO_2 output is sampled during midday (10–18 LST), averaged across all Alaskan land grid points (55° N to 72° N, 170° W to 140° W), and binned vertically into the ML and FT. We run CO_2 experiments based on two configurations of the Community Land Model, version 4.5 (CLM4.5) (15–17). These experiments are described briefly below and in more detail in *S2: Land and Atmospheric Simulations*.

The first experiments, denoted TRANSPORT, focus on the present day (2009–2013) to examine sensitivity of observed CO_2 seasonal cycles to Alaskan CO_2 flux. These simulations use year-specific CLM4.5 flux (18) and winds to best represent observed conditions and interannual variability. Three variants are considered: (*i*) CONTROL, a baseline run with all fluxes turned on; (*ii*) ALASKA-OFF, an Arctic influence run with Alaskan fluxes at zero for the domain (55° N to 72° N, 170° W to 140° W); and (*iii*) ARCTIC-OFF, the long-range transport run with Arctic fluxes set to zero for the domain (55° N to 90° N, 180° W to 180° E).

The second set of experiments focuses on the ability of current observing strategies to detect changes in CO_2 flux patterns resulting from projected climate-induced changes in the ABZ carbon cycle. These simulations use time-varying winds from 2000 to 2010 and six sets of decadal CLM4.5 fluxes for present day (HIST, 1990–2010) and future (15YR, 2005–2015; 30YR, 2020–2030; 50YR, 2040–2050; 100YR, 2090–2100; 200YR, 2190–2200) scenarios. Present day and future scenarios are further divided into simulations to test CO_2 sensitivity to flux changes in Alaska (ALASKA-ON), in the Arctic (ARCTIC-ON), and at global scale (GLOBAL-ON). CLM4.5 is configured as described in two recent permafrost studies (19, 20) and forced by time-varying meteorology corresponding to historical and future climates (Fig. S6 and *S2: Land and Atmospheric Simulations*), with modeled photosynthesis driven by constant preindustrial CO_2. We consider two scenarios for permafrost thaw. The first, denoted FUTURE-DEEP, assumes that deep permafrost carbon is active (19). In the second, denoted FUTURE-SHALLOW, deep soil decomposition is disabled by varying a parameter Z_τ in CLM4.5, which controls decomposition rates as a function of soil depth. These experiments decouple changing dynamics of surface soils from deep soils and isolate the potential contributions from permafrost layers (19).

Results and Discussion

Observing CO_2 Signals over Alaska. Alaskan airborne and satellite datasets show a similar range of seasonal and interannual variability throughout the ML, FT, and column but exhibit key differences in seasonal cycle amplitude and phase in the multiyear average and throughout the vertical column (Fig. 1 *A–C*, Fig. S7, and *S1: Observed CO_2*), including a wide range of dates for spring and fall zero crossing and amplitudes of spring enrichment and summer depletion. These differences are attributed to the range of

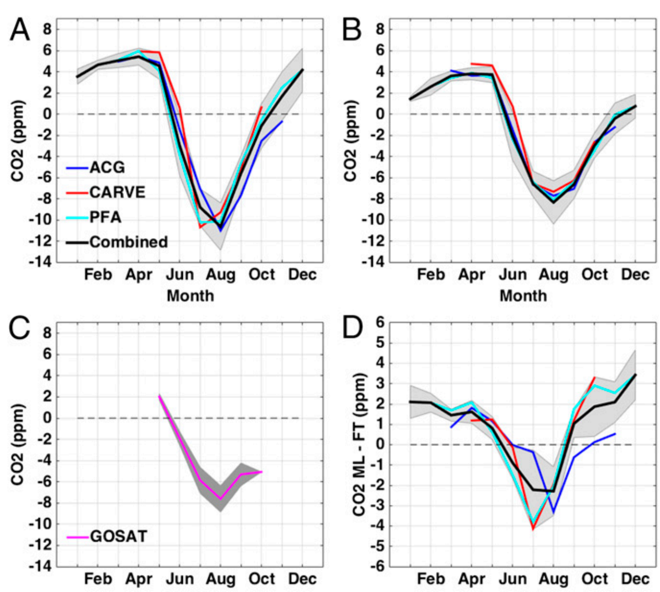

Fig. 1. Observed CO_2 seasonal cycles from satellite and airborne instruments. Shown are individual (color) and combined (black) observations averaged from 2009 to 2013 for (*A*) FT (3–7 km asl), (*B*) ML (0–3 km asl), (*C*) column average, and (*D*) vertical gradient (difference between ML and FT). Shading is the monthly SD and represents interannual variability over 5 y. Values are monthly averages, and grid lines represent middle of month.

sampling strategies used. For example, PFA resolves the full annual cycle but with low spatial sampling (essentially a fixed point), whereas ACG and CARVE have high spatial sampling but different footprints throughout the ML and FT (Figs. S1 and S2). ACG, CARVE, and GOSAT provide spatial sampling across the growing season and transition seasons but with reduced sampling during transition seasons. Compared with ACG, CARVE samples at higher spatial resolution, at lower average altitude in the ML and FT, and with a footprint focused more on the Alaskan interior, leading to different summer drawdown patterns. However, ACG, PFA, and GOSAT sample over multiple consecutive years (2009–2013), whereas this study only used CARVE data from 2012 to 2013. These results suggest that current airborne and satellite strategies capture key aspects of the Alaskan carbon cycle but that individual campaigns are unlikely to constrain regionally and seasonally integrated carbon balance changes because of the wide range of spatial and temporal variability throughout the ML and FT.

Averaging across airborne datasets from 2009 to 2013 combines the strengths of each observing strategy to better characterize seasonal carbon cycle behavior (Fig. 1 and Fig. S8*A*). The composite shows a linear decrease in seasonal cycle amplitude from 17.4 ± 3.5 parts per million (ppm) in the ML to 13.6 ± 3.5 ppm in the FT and lengthening of net carbon uptake period (time between spring and fall zero crossing) from 137 ± 16.4 d to 159 ± 9.24 d through delayed fall zero crossing at larger spatial scales (increasing spatial footprint). Column data from GOSAT show a similar pattern of reduced seasonal cycle amplitude, longer growing season carbon uptake period, and delayed fall zero crossing moving to progressively larger spatial scales (Alaska, pan-Arctic, and midlatitudes). In contrast, spring zero crossing dates show minimal variability (within 2 d) across airborne and satellite datasets.

Despite improved representation of regional carbon cycle changes in Alaska in combined airborne data, TRANSPORT simulations indicate that CO_2 signals in the ML, FT, and column are strongly masked by long-range transport from both the pan-Arctic and lower latitudes (*S3: Long-Range Transport*). For example, the large observed difference in zero crossing dates in fall relative to the small difference in spring zero crossing is a function of the difference between the transport and Alaskan components of seasonal cycle amplitude. Spring source–sink transition occurs earlier in midlatitudes than at high latitudes, but transport delays propagation of midlatitude signals to Alaska, such that the ML and FT experience spring depletion at the same time. In contrast, the fall sink–source transition occurs earlier at high latitudes, whereas transport delays midlatitude signals, thus leading to the large timing difference in fall zero crossing days in the ML and FT. TRANSPORT runs that zero CO_2 fluxes in Alaska (ALASKA-OFF) and pan-Arctic (ARCTIC-OFF) show delays of 1 and 2 wk, respectively, in fall zero crossing relative to CONTROL. These runs also suggest that Alaskan fluxes contribute less than 10% to observed seasonal amplitude over Alaska (*S3: Long-Range Transport*) (11, 12).

We find that the CO_2 vertical gradient, defined as the difference between ML and FT CO_2, gives a robust measure of Alaskan CO_2 fluxes, because subtracting FT from ML CO_2 reduces the influence of long-range transport. In combined airborne observations, the seasonal amplitude of the vertical gradient is 4–5 ppm (Fig. 1*D*). Peak depletion in the CO_2 vertical gradient occurs by or before August, similar to ML and FT CO_2, but has more rapid enrichment and earlier zero crossing in fall, indicative of a stronger local influence. Comparing individual airborne datasets shows earlier and deeper spring drawdown and more rapid fall enrichment in CARVE and PFA compared with ACG. CONTROL reproduces key seasonal (Fig. 2*A*) features of combined observations, including seasonal amplitude, zero crossing dates, and peak summer depletion, and interannual features during summer attributed to variations in CO_2 flux ($r = 0.88 \pm 0.28$) (Fig. S9). The timing and magnitude of simulated spring depletion are more consistent with CARVE and PFA than ACG. This anomaly in ACG is likely the result of sparse sampling in the Alaskan ML (Fig. S2), which reduces sensitivity to

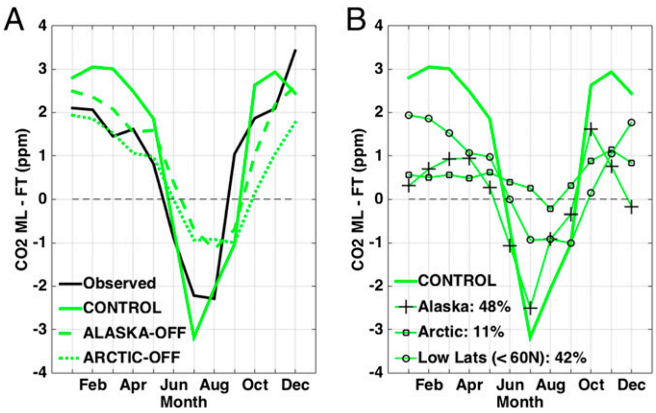

Fig. 2. Sensitivity of CO_2 vertical gradient to long-range transport vs. Alaskan CO_2 flux. (*A*) Observed (black) and simulated (green) seasonal cycles. Observations are based on combined airborne datasets from Fig. 1*D*. Simulations are based on TRANSPORT experiments for CONTROL (solid), ALASKA-OFF (dashed), and ARCTIC-OFF (dotted). (*B*) Regional contributions to CONTROL (solid) for Alaska (+), pan-Arctic (□), and low latitudes (○) estimated as the difference between TRANSPORT experiments in *A*. Lines represent seasonal average from 2009 to 2013.

Alaskan CO_2 fluxes, and highlights the importance of spatially distributed airborne sampling in the continental interior ML.

Degradation of simulated amplitude and phase in ALASKA-OFF and ARCTIC-OFF supports a strong contribution of Alaskan CO_2 fluxes to observed vertical gradients in Alaska. We estimate that 48% of the CONTROL amplitude is driven locally (CONTROL − ALASKA-OFF) compared with 11% from the pan-Arctic (CONTROL − ARCTIC-OFF) and 41% from low latitudes (ARCTIC-OFF) (Fig. 2*B*). Taken together, we find that Alaskan fluxes drive a short but intense carbon uptake period, with CO_2 depletion in early summer and enrichment in late summer to early fall. These fluxes are subject to interannual variations driven by observed climate anomalies (13), which are reflected in vertical CO_2 gradients (Fig. S9), highlighting a need for year-round airborne profiles sustained over multiple consecutive years to disentangle rapid changes in uptake from slow persistent changes.

Detecting Future Carbon Balance Signals. The experiments above show that Alaskan CO_2 fluxes produce observable signals in the vertical gradient of atmospheric CO_2. Given trends of intensifying seasonal CO_2 amplitude since 1960 (7) and projected intensification with climate warming (19), a critical question is how future climate-induced ABZ carbon cycle changes will manifest themselves and whether these changes produce CO_2 signals that are detectable in the presence of interannual variability. We investigate the detectability of climate-induced carbon balance changes by analyzing CO_2 vertical gradients forced by CLM CO_2 flux projections. We focus our analysis on the response to changing climate in the absence of the confounding effect of carbon fertilization, which leads to large differences in uptake depending on nutrient limitation (19), although we also show patterns in the presence of this effect (Fig. S6).

Climate change simulations with an active deep permafrost carbon layer (FUTURE-DEEP) indicate a slight increase in total annual emissions in Alaska from near carbon-neutral conditions in 1990–2010 to a moderate source (0.05 Pg C y^{-1}) in 15–50 y and a strong source (0.15 Pg C y^{-1}) in 100–200 y and strong amplification of seasonal exchange, with earlier spring uptake, stronger summer uptake, earlier/stronger fall/winter emissions, and a shift of peak emissions from September to October (Fig. 3*A*) as the phase lag of heat conduction shifts decomposition of deep soil carbon later into fall and winter (19).

Atmospheric simulations driven by projected CO_2 flux changes in Alaska and fluxes outside Alaska fixed to the period 1990–2000 (ALASKA-ON) show corresponding increases in the seasonal amplitude (fall − summer) of Alaskan CO_2 vertical gradients (Fig. 3*B*),

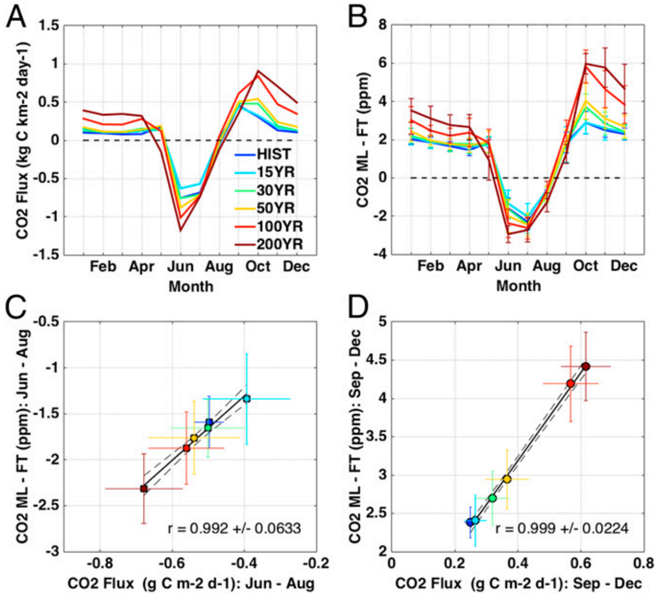

Fig. 3. Modeled CO_2 sensitivity to future warming and permafrost thaw. (*A*) CLM4.5 CO_2 flux for projected warming scenarios in Alaska: HIST (1990–2000; dark blue), 15YR (2005–2015; light blue), 30YR (2020–2030; green), 50YR (2040–2050; yellow), 100YR (2090–2100; light red), and 200YR (2190–2200; dark red). (*B*) CO_2 vertical gradient for warming scenarios in *A*. (*C*) Regression of CO_2 vertical gradient summer minimum (June to August) against summer CO_2 flux. (*D*) Same as *C* but for fall (September to December).

rising from 3.97 ± 0.36 ppm initially to 6.73 ± 0.61 ppm in 2200. Enhanced summer depletion (stronger negative gradient) is correlated with increased uptake from June to August (Fig. 3*C*), and enhanced fall enrichment (stronger positive gradient) is correlated with increased emissions from September to December (Fig. 3*D*). Summer signals show reduced depletion over the first 15 y as respiration outpaces photosynthesis and then, enhanced depletion as growing conditions improve in 15–200 y. Fall CO_2 signals increase slowly at first (0–50 y) as decomposition of deep soil carbon is delayed by low liquid moisture and oxygen availability and then, more rapidly (50–200 y) after initial active layer deepening is established.

A key result is that climate-induced CO_2 signals increase more rapidly (relative to HIST) and significantly (compared with interannual variability) in fall than summer. Comparing the months of strongest enrichment (October) with those of strongest depletion (June) shows a factor of three stronger change over 50 y (50YR − HIST; fall CO_2 increase of 1.14 ± 1.12 ppm vs. summer decrease of 0.41 ± 1.0 ppm), a factor of four stronger change over 100 y (100YR − HIST; 2.94 ± 1.04 ppm vs. 0.79 ± 0.92 ppm), and a factor of two stronger change over 200 y (200YR − HIST; 3.08 ± 0.79 ppm vs. 1.35 ± 0.70 ppm). Strong CO_2 interannual variability is likely to mask most of the summer signal over the next 100 y, whereas regional-scale changes in fall may be detectible in as early as 30 y (30YR − HIST = 0.83 ± 0.89 ppm in October). These results indicate that a hypothetical observing system, with perfect spatial and temporal sampling over Alaska, has high likelihood of detecting projected slow regional carbon balance impacts in fall in the next 30–50 y and low likelihood of detecting summer impacts over the next 200 y.

To test the ability of current observing systems to detect predicted carbon balance changes given known temporal and spatial sampling limitations, we sample simulated CO_2 concentrations in 100YR based on the timing and methods of CARVE, PFA, ACG, and GOSAT observations collected in 2012. We then compare the corresponding, subsampled "observed" mean with the "true" mean calculated from sampling all Alaskan land points (Fig. 4*A*). Current airborne and satellite sampling strategies capture general patterns of enhanced summer depletion and cold season enrichment in 100 y. However, airborne strategies show a range of variability in the depth and timing of summer CO_2 depletion, leading to biases in estimates of regional mean drawdown from April to September, which are smallest for CARVE sampling [root mean square error (RMSE) = 0.23 ppm] and largest for PFA (RMSE = 0.38 ppm). Spring and fall transitions represent periods of largest spreads across sampling strategies. PFA, the only system to measure continuously through the entire cold season, shows increased bias in winter (RMSE = 0.76 ppm). All strategies, including GOSAT, capture but underestimate peak enrichment in October. In general, the combined airborne strategy reduces bias during overlapping sampling from April to October (RMSE = 0.24 ppm), with the largest improvements during the growing season (June to August) but with cold season sampling biases that underestimate fall respiration (September to October) and overestimate winter respiration (December to March).

Spatial gradients have an important influence on detection of regional CO_2 fluxes by the current observing network. Summer fluxes, with a relatively modest ∼1 ppm southwest to northeast positive CO_2 gradient (Fig. 4*C*) driven by increasing emissions in northeast Alaska and increased uptake in southwest Alaska (Fig. S10*A*), are well-characterized by the spatially diverse set of airborne and satellite strategies. Conversely, winter shows spatially homogenous increases in emissions across western and northern Alaska (Fig. S10*B*) but locally strong CO_2 vertical gradients north of the Brooks Range along the North Slope (4 ppm relative to annual mean) (Fig. 4*D*). These gradients are likely enhanced by shallow winter MLs, and CLM4.5 shows potential for additional enhancement by increased fall respiration associated with CO_2 fertilization (Fig. S6*B*). These results suggest that future cold season emissions in the interior North Slope may go unobserved by the 2012 observing network, despite measurements by ACG along the north coast (Fig. S2*D*) and PFA in central Alaska because of low sensitivity of current observations to this region.

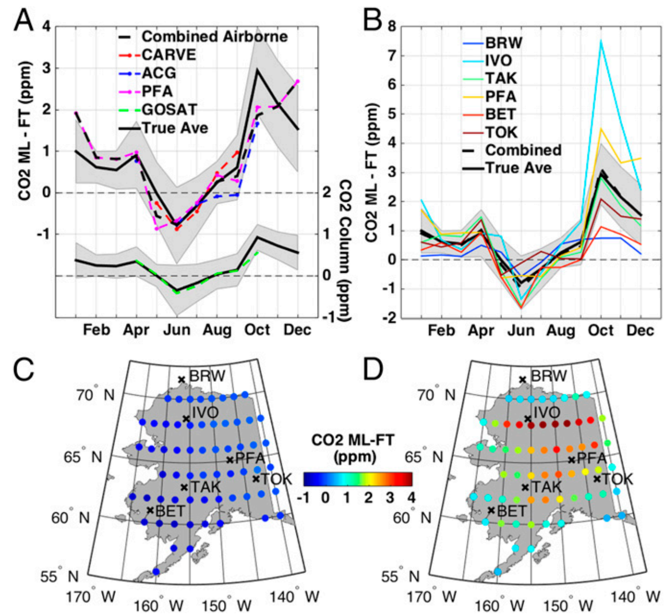

Fig. 4. Hypothetical CO_2 seasonal cycle changes based on CARVE, ACG, and PFA sampling under future warming scenarios. (*A*) Difference in CO_2 vertical gradient seasonal cycle between 100YR and HIST (100YR − HIST) based on the average of all Alaskan grid points [solid black, true average (True Ave)] and grid points likely to be sampled based on current airborne (red, CARVE; blue, ACG; magenta, PFA), satellite (green, GOSAT), and combined airborne (dashed black) strategies. (*B*) Same as *A* but for the theoretical network of fixed point airborne flask locations shown in *C* and *D*. (*C*) Map of *A* for summer average (June to August). (*D*) Map of *A* for fall average (September to December). BET, Bethel; IVO, Ivotuk; TAK, Takotna; TOK, Tok.

These results argue for a more strategic, spatially distributed observing network that samples the full annual cycle to ensure detection of changing cold season emissions and resolve annual carbon budgets. The existing network of "stationary" sites includes PFA and two tall tower sites not analyzed in this paper: the Barrow (BRW) tower along the North Slope coast and the CARVE (CRV) tall tower north of Fairbanks, AK. These tower sites have been running since 1973 and 2011, respectively, delivering key long-term, continuous (approximately hourly), high-density measurements in the ML needed to fill 2-wk sampling gaps and provide a temporal context for airborne data (21). However, the calculated footprints of these sites indicate that portions of western and eastern Alaska and the North Slope uplands have very little influence on these observations.

Considering the relative affordability and seasonal continuity of fixed point airborne sampling relative to intensive campaigns, such as CARVE, we test strategies for augmented airborne airborne vertical profiles to fill spatial gaps poorly sampled by the PFA–CRV–BRW network. We consider a network with five additional airborne vertical profile locations sampling at regular 2-wk intervals from the surface to 8 km (~500 mb) and distributed across Alaska (Fig. 4 *B–D*) at locations with existing and/or historical measurements (tall tower, flux tower, or airborne campaigns) and infrastructure (airports and cell phone towers). BRW and Ivotuk represent the North Slope coast and upland tundra, respectively. Bethel and Takotna represent the Yukon Delta and western interior, respectively. PFA represents the continental interior, and Tok provides a background site in the eastern interior.

The signals from the augmented network of fixed point airborne sites exhibit significant variability from October to December, but together, they capture mean patterns of summer drawdown and cold season emissions with negligible bias (Fig. 4*B*). The Ivotuk site (or any upland tundra site along the southern edge of the North Slope) provides a key source of new information for the North Slope tundra and captures a factor of two greater local fall respiration enrichment compared with the regional mean (7.2 vs. 3.0 ppm in October), suggesting a strong likelihood for detecting local changes on earlier timescales (0–30 y) than at regional scales (30–50 y), especially in the case of respiration amplified by CO_2 fertilization. The coastal sites BRW and Bethel as well as Tok constrain continental and background air entering Alaska and may help to identify changing source regions under changing atmospheric transport regimes.

Dedicated carbon observing satellites, such as GOSAT, provide essential geographical coverage within Alaska and at the pan-Arctic scale that is missing or poorly sampled by sparse tall tower and airborne measurements. However, GOSAT, Orbiting Carbon Observatory-2, and other satellites that rely on passive near-IR techniques for measuring total column CO_2, including missions using highly elliptical orbits to obtain dense high-latitude sampling (22), require sunlight reflected from the Earth's surface and thus, return poor sample yield during the long, dark cold season. Even for cold season measurements, passive IR techniques are challenged by signals in large air masses because of high solar zenith angles. Thermal IR sounders, such as Atmospheric Infrared Sounder, Infrared Atmospheric Sounding Interferometer, and Thermal Emission Spectrometer, provide year-round coverage but sample the mid- to upper troposphere (700–500 mb) and do not provide ML sensitivity (23). Active CO_2 sensors (24) offer promise for year-round performance in high latitudes but have not yet shown the required precision or technical maturity for long-term ground-, airborne-, or space-based deployment.

Further complicating carbon balance detectability for satellite, airborne, and surface measurements is that climate change outside Alaska is likely to drive CO_2 flux changes that obscure Alaskan signals. Warming scenarios in CLM4.5 drive increased summer uptake and winter emissions across the pan-Arctic but opposite changes in midlatitudes, including reduced summer uptake and winter emissions (Fig. S10 *A* and *B*). Compared with ALASKA-ON, pan-Arctic climate change (ARCTIC-ON) drives an additional 0.3–0.8 ppm summer CO_2 depletion and 2–3 ppm winter enrichment (Fig. S10 *C* and *D*). Global climate change (GLOBAL-ON) drives an additional 1 ppm summer depletion, despite reduced uptake in lower latitudes, with negligible changes in winter enrichment (Fig. S10*E*). However, increased summer depletion is an artifact of CO_2 vertical gradients, where transport from reduced uptake regions in lower latitudes leads to a lower rate of FT CO_2 depletion compared with the ML (Fig. S10*H*). Thus, the influence of confounding climate effects from multiple source regions demands analysis of separate FT and ML changes as a context to interpret vertical gradients. Our results strongly argue for use of year-round airborne vertical profiles as an important constraint for regional carbon balance changes.

Detecting Emerging Carbon Sources. Analysis of permafrost carbon–climate feedback indicates that the permafrost region is highly sensitive to the decomposition of subsurface permafrost layers, with climate driven losses across the pan-Arctic by the year 2200 totaling 71–166 Pg C depending on the decomposability of deep carbon (19). In the weak carbon loss scenario (~0.5 m), deep layers remain undecomposed, with respiration limited to shallow soils. For strong carbon loss, deeper permafrost carbon (~10 m) is much more vulnerable to decomposition on warming. Because the processes controlling the rate and extent of deep permafrost thaw are highly uncertain, models cannot project the timing or magnitude of permafrost carbon release accurately (19, 25, 26). Therefore, CO_2 observing strategies designed to monitor changes in Arctic respiration patterns will be needed to avoid the risk of emerging permafrost carbon sources going undetected.

We test whether hypothetical airborne CO_2 observing strategies with continuous spatial and temporal sampling can distinguish surface from subsurface exchange to detect permafrost losses across the pan-Arctic by comparing CO_2 seasonal cycles for FUTURE-SHALLOW (Z_τ = 0.5 m) and FUTURE-DEEP (Z_τ = 10 m) for pan-Arctic–scale emissions (ARCTIC-ON). Differences in summer sink strength between these scenarios are negligible because of the seasonal delay of thermal diffusion to deeper soils but lead to stronger fall emissions in FUTURE-DEEP (Fig. S6). The projected CO_2 response shows similar summer depletion in HIST, 15YR, 30YR, and 50YR (Fig. 5 *A–D*) and slightly enhanced depletion in 100YR and 200YR (Fig. 5 *E* and *F*); however, these signals are not significantly different from each other because of low signal to noise, and they do not change significantly as the ABZ evolves to a warmer world.

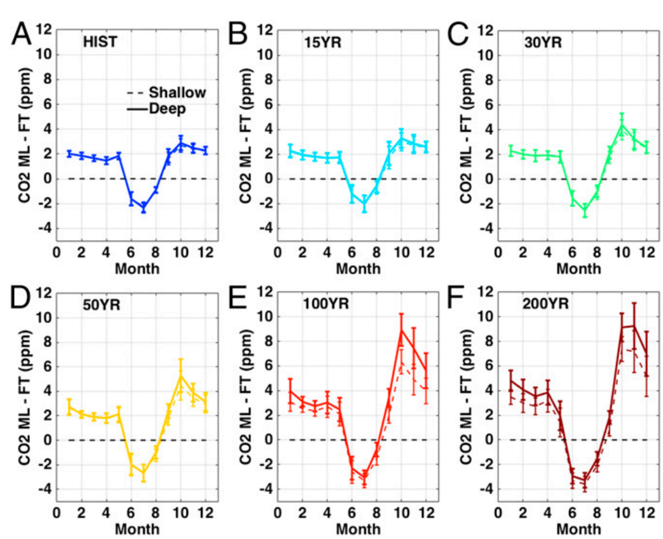

Fig. 5. CO_2 seasonal cycle changes in Alaska for shallow and deep permafrost carbon emission scenarios. CO_2 vertical gradient for FUTURE-SHALLOW (dashed lines) and FUTURE-DEEP (solid lines) permafrost scenarios shown for (*A*) HIST, (*B*) 15YR, (*C*) 30YR, (*D*) 50YR, (*E*) 100YR, and (*F*) 200YR based on experiments with pan-Arctic fluxes turned on (ARCTIC-ON).

Fall enrichment is similar until 100YR, after which signals caused by deep permafrost loss increase significantly compared with shallow loss, including 2.0- to 2.5-ppm difference from October to December.

These results suggest that the current airborne strategies are unlikely to disentangle signals from shallow and deep soil emissions in summer but could potentially detect deep permafrost carbon emissions in fall with improved temporal and spatial sampling. However, simultaneous respiration of shallow surface carbon and amplification by CO_2 fertilization and fire emissions is likely to mask deep permafrost emissions from a CO_2 observing system. Radiocarbon data, which can be used to partition respiration into autotrophic and heterotrophic young and old soil components (27), may provide a viable solution to disentangle and track future emissions from deep permafrost.

Conclusions

The seasonal amplitude of CO_2 has been increasing in northern high latitudes over the past five decades (7). The ability to quantify ABZ contributions has been limited by the lack of long-term atmospheric CO_2 observations with sufficient temporal, vertical, or spatial resolution to constrain annual carbon budgets at the regional scale. Current airborne and satellite strategies are beginning to address some of these shortcomings with close monitoring of changing sink activity in the growing season. However, emerging carbon–climate feedbacks driven by warming, CO_2 fertilization, and fires are likely to reshape our understanding of the Arctic carbon cycle, such that earlier and stronger sinks are offset by enhanced sources. CO_2 and CH_4 emissions related to permafrost thaw and increasing biotic activity are unlikely to manifest themselves until later in the cold season (20, 28), shifting the ABZ to an irreversible carbon source that would go undetected by current sampling strategies and measurement systems until long after the onset of permafrost thaw.

The evolving ABZ biosphere and threat of unobserved cold season emissions call for a more comprehensive observing system focused on (*i*) year-round, (*ii*) vertically resolved, and (*iii*) spatially distributed sampling. Our analysis indicates that these three key objectives can be met by a network of airborne vertical profiles distributed across Alaska; however, the combination of tall tower continuous measurements, intensive airborne campaigns, and satellite remote sensing can significantly augment this network by providing temporal and spatial context. Based on existing technology and operating costs, we expect that a network of airborne profiles complemented by tall towers and satellite remote sensing will ensure that emerging carbon sources and sinks do not go undetected.

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